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Fretting corrosion of tin-plated contacts

Young Woo Park[a], T.S.N. Sankara Narayanan[b], Kang Yong Lee[a,*]

[a]Stress Analysis and Failure Design Laboratory, School of Mechanical Engineering, Yonsei University, Seoul 120-749, Republic of Korea
[b]National Metallurgical Laboratory, Madras Centre, CSIR Complex, Taramani, Chennai-600 113, India

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Abstract

The susceptibility of tin-plated contacts to fretting corrosion is a major limitation for its use in electrical connectors. The present paper evaluates the influence of a variety of factors, such as, fretting amplitude (track length), frequency, temperature, humidity, normal load and current load on the fretting corrosion behaviour of tin-plated contacts. This paper also addresses the development of fretting corrosion maps and lubrication as a preventive strategy to increase the life-time of tin-plated contacts. The fretting corrosion tests were carried out using a fretting apparatus in which a hemispherical rider and flat contacts (tin-plated copper alloy) were mated in sphere plane geometry and subjected to fretting under gross-slip conditions. The variation in contact resistance as a function of fretting cycles and the time to reach a threshold value (100 mΩ) of contact resistance enables a better understanding of the influence of various factors on the fretting corrosion behaviour of tin-plated contacts. Based on the change in surface profile and nature of changes in the contact zone assessed by laser scanning microscope (LSM) and surface analytical techniques, the mechanism of fretting corrosion of tin-plated contacts and fretting corrosion maps are proposed. Lubrication increases the life-time of tin-plated contacts by several folds and proved to be a useful preventive strategy.

Keywords: Fretting; Oxidation; Surface analysis; Lubrication; Fretting corrosion maps

1. Introduction

Fretting, an accelerated surface damage that occurs at the interface of contacting materials subjected to small oscillatory movement is a common problem in many engineering applications. The deleterious effect of fretting in electrical connections assumes significance as it influences the reliability and system performance [1]. Tin-plated contacts are highly susceptible for fretting corrosion and it is a major limitation for their use in electrical connectors [2–5]. Though fretting itself may not result in failure of an electrical connection, the deleterious effect of fretting is a great deal of concern since fretting leads to the accumulation of the wear debris and oxidation products in the contact zone in the form of a thick highly localized insulating layer. The formation of such an insulating layer results in a rapid increase in contact resistance and eventually leads to virtually an open circuit. Though such a phenomenon evolves with time, the main difficulty in predicting is that it is influenced by many interdependent factors and it is not easy to detect. This warrants a thorough understanding of the fretting corrosion behaviour under varying experimental conditions. Since several factors influence the life-time of tin-plated contacts under fretting conditions, mapping the fretting–corrosion behaviour would be of immense help in the development of reliability models and life-time estimation approaches, to predict the life-time of connector contacts.

The development of wear mechanism maps for metals, ceramics, metal–matrix composites, polymers, coatings, fretting and erosion maps is reviewed by Lim [6]. According to Williams [7], there is no universal mechanism of wear and no simple correlation between rates of wear or surface degradation and values of friction coefficient. However, he suggests that the wear maps would assist in establishing the possible or likely modes of surface damage and how close the operating conditions are to any

*Corresponding author. Tel.: +82 2 2123 2813; fax: +82 2 2123 2813.
E-mail address: KYL2813@yonsei.ac.kr (K.Y. Lee).

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transition between mild and severe regimes of wear [7]. The development of wear map for gray cast iron, titanium nitride coated high speed steel and the sliding wear behaviour of dissimilar metallic interfaces and its relevance to understand the wear mechanism is established by many researchers [8–11]. The development of such types of maps to understand the erosion–corrosion and micro-abrasion behaviour of metals, coatings and composites is addressed by Stack and her co-workers [12–17]. Wellman and Nicholls [18] have presented an overview of high temperature erosion–oxidation mechanisms, maps and models. The concept of fretting maps is introduced by Vingsbo and Söderberg [19] to determine the relevant fretting regimes such as stick regime, mixed stick-slip regime and gross-slip regime. Elleuch et al. [20], have developed the fretting maps for anodized aluminium alloys. Running condition fretting maps for WC–Co and TiN coatings have been constructed by Carton et al. [21] and Wei et al. [22]. The development of fretting maps for connector contacts has not been explored much. A map detailing the various damage mechanisms sustained by silver-plated copper contacts is proposed by Kassman and Jacobson [23]. According to them, such a map is not only useful in design but also in failure analysis as well.

The present paper aims to address the influence of a variety of factors, such as fretting amplitude (track length), frequency, temperature, humidity, normal load and current load on the performance of tin-plated contacts, the development of fretting corrosion maps for life-time prediction and the effectiveness of lubrication as a preventive strategy to increase the life-time of tin-plated contacts.

2. Experimental details

The fretting corrosion behaviour of tin-plated contacts was studied using a fretting apparatus in which the relative motion between the contacts was provided by a variable speed motor/precision stage assembly. The schematic of the fretting apparatus used in this study is given in Fig. 1(a). The normal contact force was supplied by the weights placed on the balance arm. The contacts were flat verses 1.5 mm radius hemispherical rider (Fig. 1(b)), both of them were made of copper alloy (Ni-1.82%, Si-0.75%; Zn-0.01%; Sn-0.37% and Cu-balance) and electroplated with tin to a thickness of 3 μm, supplied by the Korea Electric Terminal Company Ltd., Korea. The rider and flat specimens were degreased using acetone in an ultrasonic cleaner, dried and carefully mounted in the fretting test assembly. The rider and flat contacts were mated in such a way to create a point contact in "sphere plane" geometry. The contact geometry and the circuit used to measure the contact resistance are shown in Fig. 1(b). The experimental conditions used are given in Table 1. The fretting tests were conducted under gross-slip conditions. The contact resistance was continuously measured as a function of fretting cycles. After testing, the surface profile, surface roughness across the fretted zone and the wear depth were assessed using a Carl Zeiss laser scanning microscope (LSM) (Model: LSM-5 PASCAL). Scanning electron microscopy

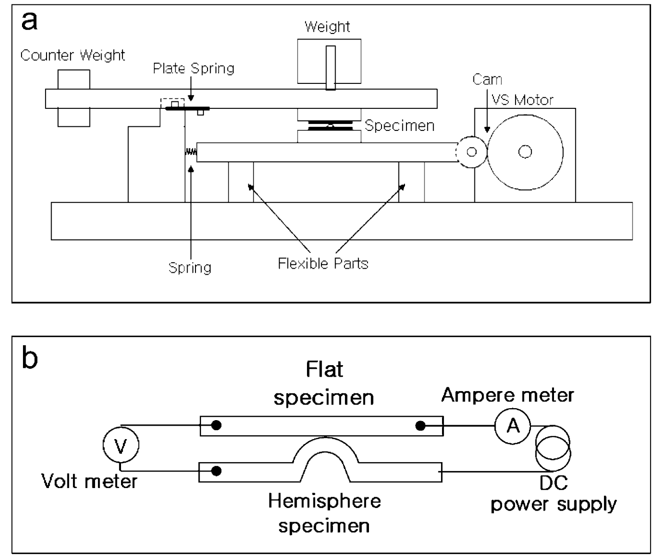


Fig. 1. (a) Schematic of the fretting apparatus used in the present study and (b) the geometry of the rider and flat samples and the circuit used to measure the contact resistance.

Table 1
Test conditions used to study the fretting corrosion behaviour of tin-plated contacts

Variable	Range
Frequency	3, 5, 7, 10, 15 and 20 Hz
Amplitude	±5, ±25, ±50 and ±90 μm
Load	0.1, 0.5, 1 and 2 N
Temperature	27, 55, 65, 75, 85, 105, 125, 155 and 185 °C
Humidity	20–45% RH, 45–75% RH, >85% RH
Current load	0.1, 0.5, 1.0, 1.5, 2.0 and 3.0 A

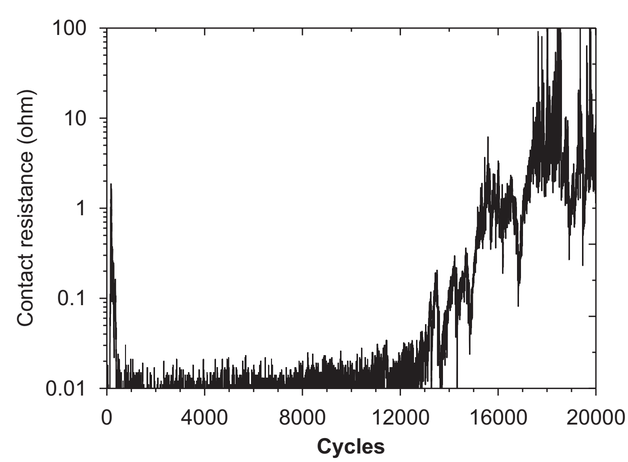


Fig. 2. Change in contact resistance of tin-plated copper alloy contact measured across the contact zone as a function of fretting cycles. (Frequency: 10 Hz; amplitude: ±90 μm; temperature: 27 °C; humidity: 45% RH; normal load: 0.5 N and current load: 0.1 A.)

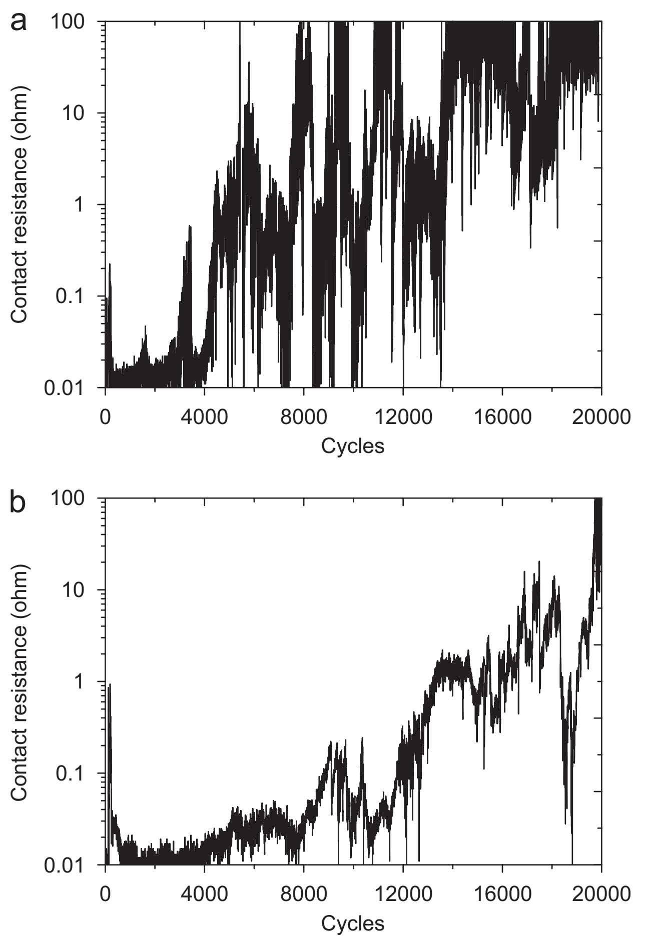


Fig. 3. Change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at different frequencies (a) 3 Hz and (b) 20 Hz. (Amplitude: $\pm 25\,\mu m$; temperature: 22 °C; humidity: 55% RH; normal load: 0.5 N and current load: 0.1 A.)

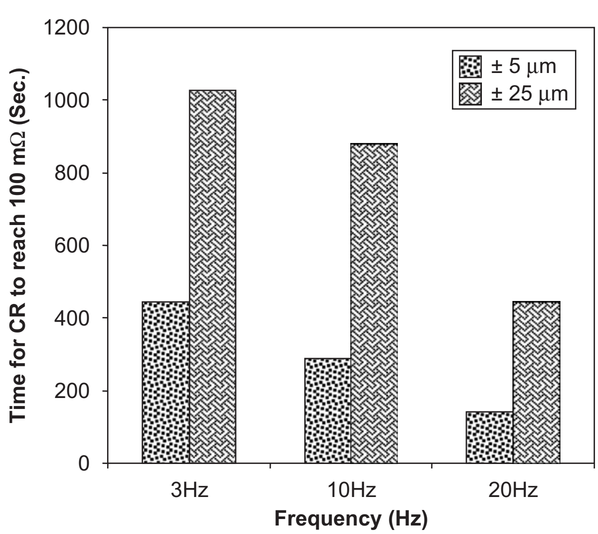


Fig. 4. Plot of time required for the contact resistance to reach a threshold value of $100\,m\Omega$ for the track lengths of $\pm 5\,\mu m$ and $\pm 25\,\mu m$ at three different fretting frequencies of 3, 10 and 20 Hz. (Amplitude: $\pm 25\,\mu m$; temperature: 22 °C; humidity: 55% RH; normal load: 0.5 N and current load: 0.1 A.)

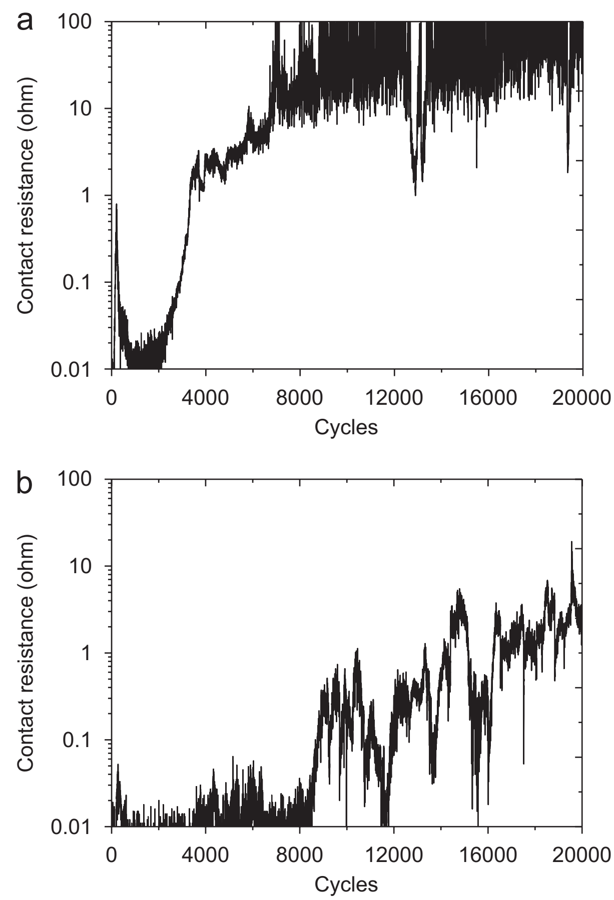


Fig. 5. Change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at different amplitudes (a) $\pm 5\,\mu m$ and (b) $\pm 25\,\mu m$. (Frequency: 10 Hz; temperature: 22 °C; humidity: 55% RH; normal load: 0.5 N and current load: 0.1 A.)

(SEM), energy dispersive X-ray analysis (EDX) and X-ray dot mapping were used to characterize the fretting damage at the contact zone. Studies were conducted in several modes including secondary electron imaging, EDX line scanning analysis across the contact zone, EDX analysis of selected regions on the contact zone and X-ray elemental dot mapping to assess the elemental distribution across the contact zone.

3. Results and discussion

3.1. Variation in contact resistance as a function of fretting cycles

The change in contact resistance of tin-plated copper alloy contacts as a function of fretting cycles, obtained using the following conditions, frequency: 10 Hz, amplitude: $\pm 90\,\mu m$, temperature: 27 °C, humidity: 45% RH, normal load: 0.5 N and current load: 0.1 A, is shown in Fig. 2. A hump is observed between 100 and 400 fretting cycles followed by a low contact resistance up to 8000 cycles. There is a slight increase in the contact resistance from 8000 to 12,000 cycles followed by a gradual increase

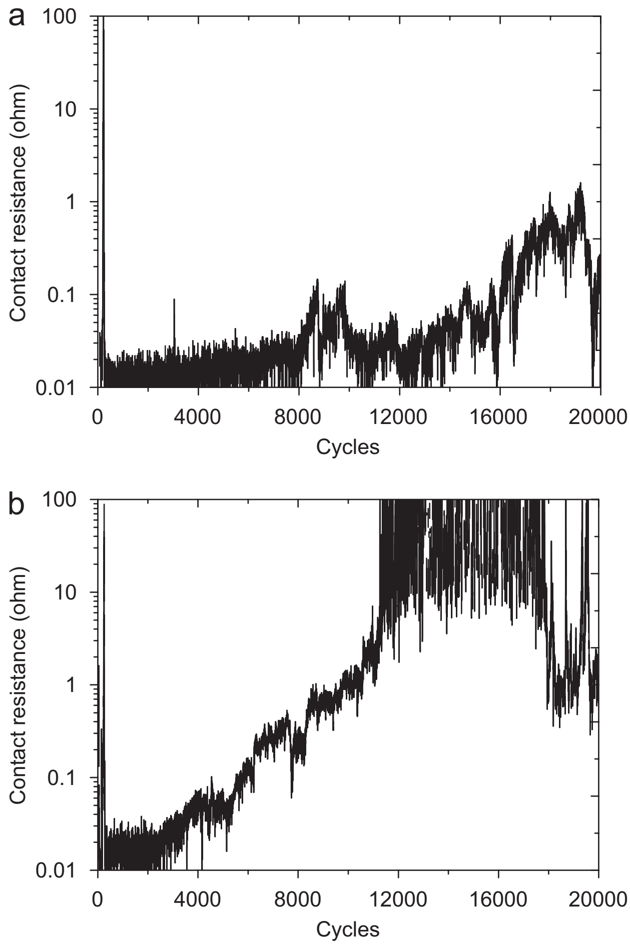


Fig. 6. Change in contact resistance of tin-plated contacts subjected to fretting at elevated temperatures as a function of fretting cycles (a) 85 °C and (b) 155 °C. (Amplitude: $\pm 90\,\mu m$; frequency: 10 Hz; humidity: 55% RH; normal load: 0.5 N and current load: 0.5 A.)

in the contact resistance from 12,000 to 15,000 cycles, beyond which the contact resistance increases rapidly. The observed trend of change in the contact resistance as a function of fretting cycles correlates well with those of other researchers [2–5]. The initial hump is due to the presence of a thin film of tin oxide on the surface of the tin-plated copper alloy contact, which is removed in a very short span of time. If the oxide film is present on the tin coating, then the contact resistance should be relatively high when the contacts are mated together. However, the contact resistance is relatively low, and the increase in the contact resistance (hump) appears only after the fretting motion is started. The observed low initial contact resistance could be explained based on the multi-spot contact model, which assumes that the metal oxide is more brittle than the metal [24]. When the tin-plated copper alloy contacts are mated together with a normal load of 0.5 N, the hard tin oxide layer (hardness: $1650\,kg/mm^2$) gets cracked and induces a stress on the softer tin coating (hardness: $5\,kg/mm^2$) lying beneath it. As a result, the softer tin coating extrudes through the cracks in the tin oxide layer and establishes a good metal-to-metal contact. The low contact resistance values observed up to 8000 cycles, after the initial hump, is due to the conducting nature of the soft tin plating. The gradual increase in the contact resistance could be attributed to the formation of tin oxide film. Subsequent rapid increase in the contact resistance is due to the accumulation of wear debris and oxidation products, which reduces the electrical conducting area, suggesting that with increase in number of fretting cycles the current is conducted through an increasingly smaller area of contact.

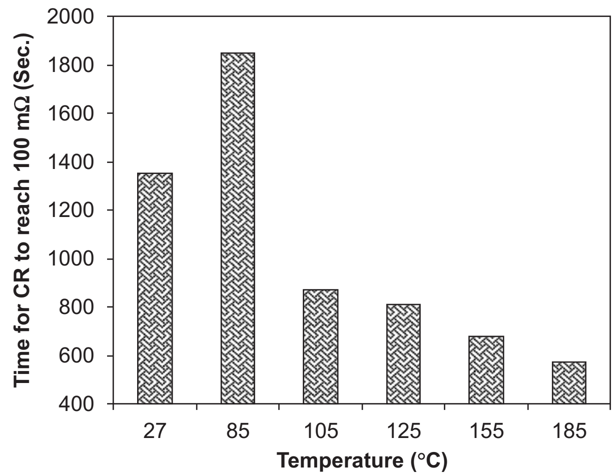


Fig. 7. Plot of time required for the contact resistance to reach a threshold value of $100\,m\Omega$ at various temperatures. (Amplitude: $\pm 90\,\mu m$; frequency: 10 Hz; humidity: 55% RH; normal load: 0.5 N and current load: 0.5 A.)

3.2. *Influence of various factors on the fretting corrosion behaviour of tin-plated contacts*

The influence of various factors on the fretting corrosion behaviour of tin-plated contacts is studied by measuring the change in contact resistance as a function of fretting cycles using various combinations of experimental conditions. The general trend in change in contact resistance as a function of fretting cycles is similar in all the cases. However, the point of failure varies a lot depending on the experimental conditions used. A threshold value of contact resistance could be used as the failure criterion and the time at which the contact resistance reaches this threshold value can be used to assess the time of failure. According to Mroczkowski [25], the choice of the threshold value of contact resistance should be made based on the application rather that the product specification. Whitley and Malucci [26] have proposed a failure criterion for electronic contacts to be $10R_c$ when neglecting film resistance (where R_c is the contact resistance for clean surface contact). Since tin and tin alloy plated contacts contains an oxide layer at the metal surface, the rule of $10R_c$ as the failure criterion does not apply for such contacts. In the present study, to compare the influence of various factors, $100\,m\Omega$ is chosen as a threshold value of contact resistance and the time to

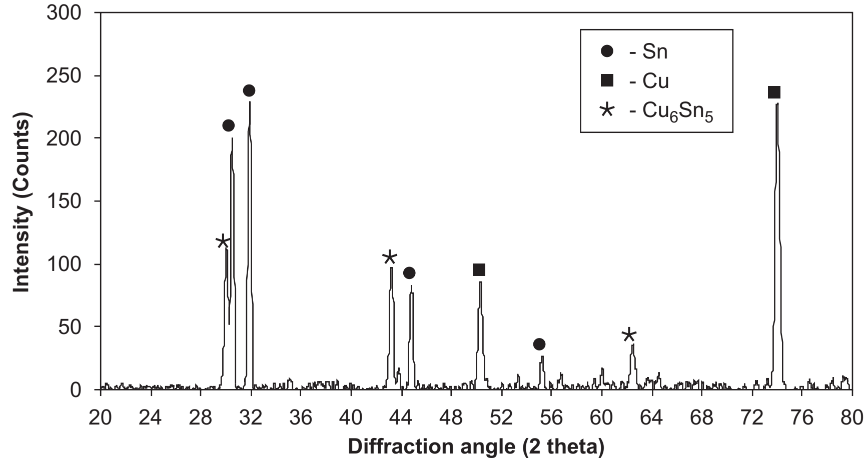
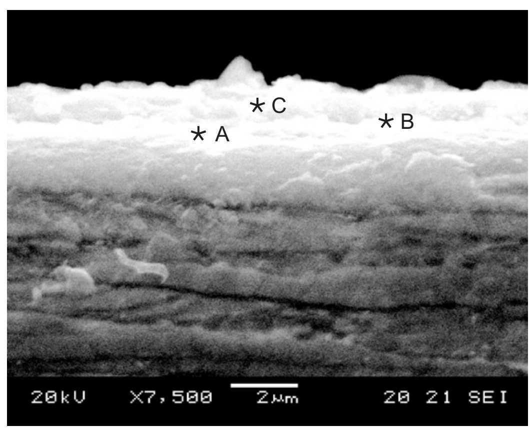


Fig. 8. XRD pattern of tin-plated contact subjected to thermal treatment at 155 °C for 30 min.



Point A			Point B			Point C		
Cu (wt.%)	Sn (Wt.%)	Assignment of phase	Cu (wt.%)	Sn (Wt.%)	Assignment of phase	Cu (wt.%)	Sn (Wt.%)	Assignment of phase
79.63	20.37	Cu_3Sn	61.80	38.20	Cu_6Sn_5	47.85	52.15	Cu_6Sn_5

Fig. 9. Scanning electron micrograph of the cross sectional view of tin-plated contact subjected to thermal treatment at 155 °C for 30 min.

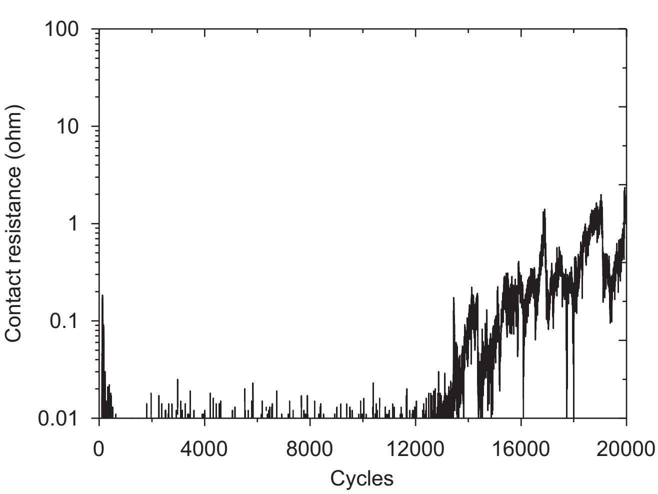


Fig. 10. Change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 65% RH. (Amplitude: ±90 μm; frequency: 10 Hz; temperature: 27 °C; normal load: 0.5 N and current load: 0.1 A.)

reach this threshold value is taken as a measure of performance.

3.2.1. Effect of fretting frequency

The effect of frequency on the fretting corrosion behaviour of tin-plated contacts is studied in the range of 3–20 Hz. The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 3 and 20 Hz are shown in Figs. 3(a) and (b), respectively. For a given track length, the threshold value of 100 mΩ is reached early at 20 Hz (Fig. 4). It is well-known that the rate of wear of the tin coating and the extent of oxidation of the contact zone are a function of fretting frequency; the rate of wear of tin coating will be high at 20 Hz whereas the extent of oxidation of the contact zone will be high at 3 Hz. Since oxidation of the contact zone is a dominant factor in deciding the rapid increase in contact resistance, one would expect that the threshold value of contact resistance will reach early at 3 Hz. But in contrast, the threshold value is

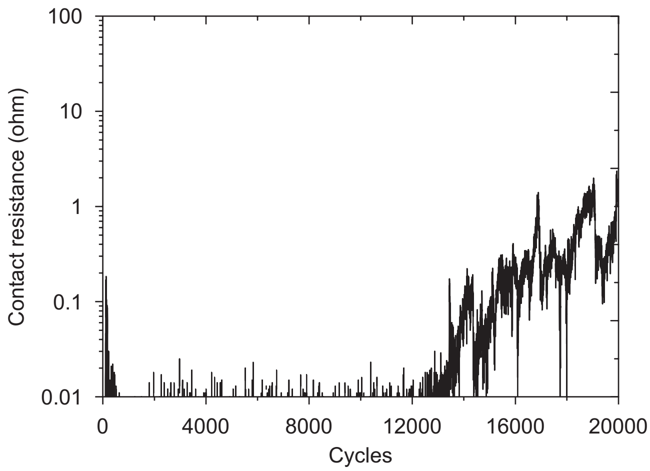


Fig. 11. Change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at a normal load of 2 N. (Frequency: 10 Hz; amplitude: $\pm 90\,\mu m$; temperature: 27 °C; humidity: 55% RH and current load: 0.1 A.)

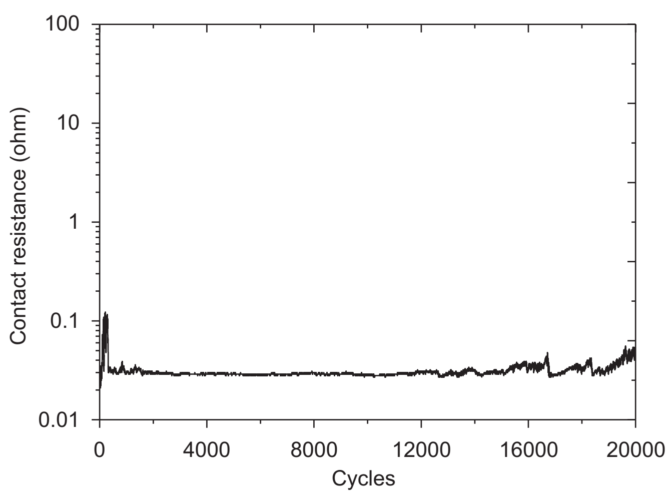


Fig. 12. Change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at a current load of 3 A. (Amplitude: $\pm 90\,\mu m$; frequency: 10 Hz; temperature: 27 °C; humidity: 53% RH and normal load: 0.5 N.)

reached early at 20 Hz. The early failure observed at 20 Hz is due to the faster removal of tin coating, which results in the formation of higher quantities of wear debris and oxidation products [27]. These observations suggest that though the extent of oxidation is relatively less at 20 Hz, the increase in the extent of accumulation of wear debris and oxidation products at the contact zone causes a rapid increase in contact resistance.

3.2.2. Effect of fretting amplitude

The effect of amplitude on the fretting corrosion behaviour of tin-plated contacts is studied in the range of $\pm 5\,\mu m$ to $\pm 90\,\mu m$ (stroke length: 10–180 μm). The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at $\pm 5\,\mu m$ and at $\pm 25\,\mu m$ are shown in Figs. 5(a) and (b), respectively. It is obvious to expect an early failure at higher amplitude of $\pm 25\,\mu m$ as the extent of oxidation is very high at higher amplitudes. However, the threshold value of 100 mΩ is reached very rapidly at lower amplitude of $\pm 5\,\mu m$ (Fig. 4). At low amplitudes, the possibility of accumulation of wear debris is very high. Accumulation of wear debris and oxidation products within a confined area causes the percolation limit for electrical conduction to reach at a shorter time and this has resulted in an earlier failure at low amplitudes of $\pm 5\,\mu m$ [27].

3.2.3. Effect of temperature

The effect of temperature on the fretting corrosion behaviour of tin-plated contacts is studied in the range of 27–185 °C [10]. The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 85 and 155 °C are shown in Figs. 6(a) and (b), respectively. It is evident from Fig. 6 that temperature has a greater influence on the extent of fretting corrosion of tin-plated contacts. The extent of oxidation increases with increase in temperature. This is also reflected in the threshold value of contact resistance, which reaches quite early with increase in temperature (Fig. 7). The softening of tin around 100 °C enables the tin-plated contact to exhibit a low contact resistance for longer fretting cycles. However, beyond 125 °C, the contact resistance increases rapidly. Besides oxidation, the formation of Cu–Sn based intermetallic compounds (IMC) at elevated temperatures also has a major influence on the performance of the tin-plated contacts. The formation of Cu–Sn based IMC is confirmed by XRD and EDX analysis (Figs. 8 and 9). The increase in rate of oxidation with increase in temperature and, the high hardness and poor electrical resistance of the Cu–Sn based IMC formed at elevated temperatures, suggests that the tin-plated contacts are unsuitable for high temperature applications [28].

3.2.4. Effect of humidity

The effect of humidity on the fretting corrosion behaviour of tin-plated contacts is studied in the range of 20–90% RH. The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 65% RH is shown in Fig. 10. The time to reach the threshold value of contact resistance suggests that the performance of the tin-plated contacts is better when the relative humidity is $>85\%$ whereas their performance is relatively poor at low humidity. At $>85\%$ RH, condensation of water vapour provides lubrication at the contact interface and enables the contact to exhibit a low contact resistance for longer fretting cycles.

3.2.5. Effect of normal load

The effect of normal load on the fretting corrosion behaviour of tin-plated contacts is studied in the range of 0.1–2.0 N. The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 2 N is

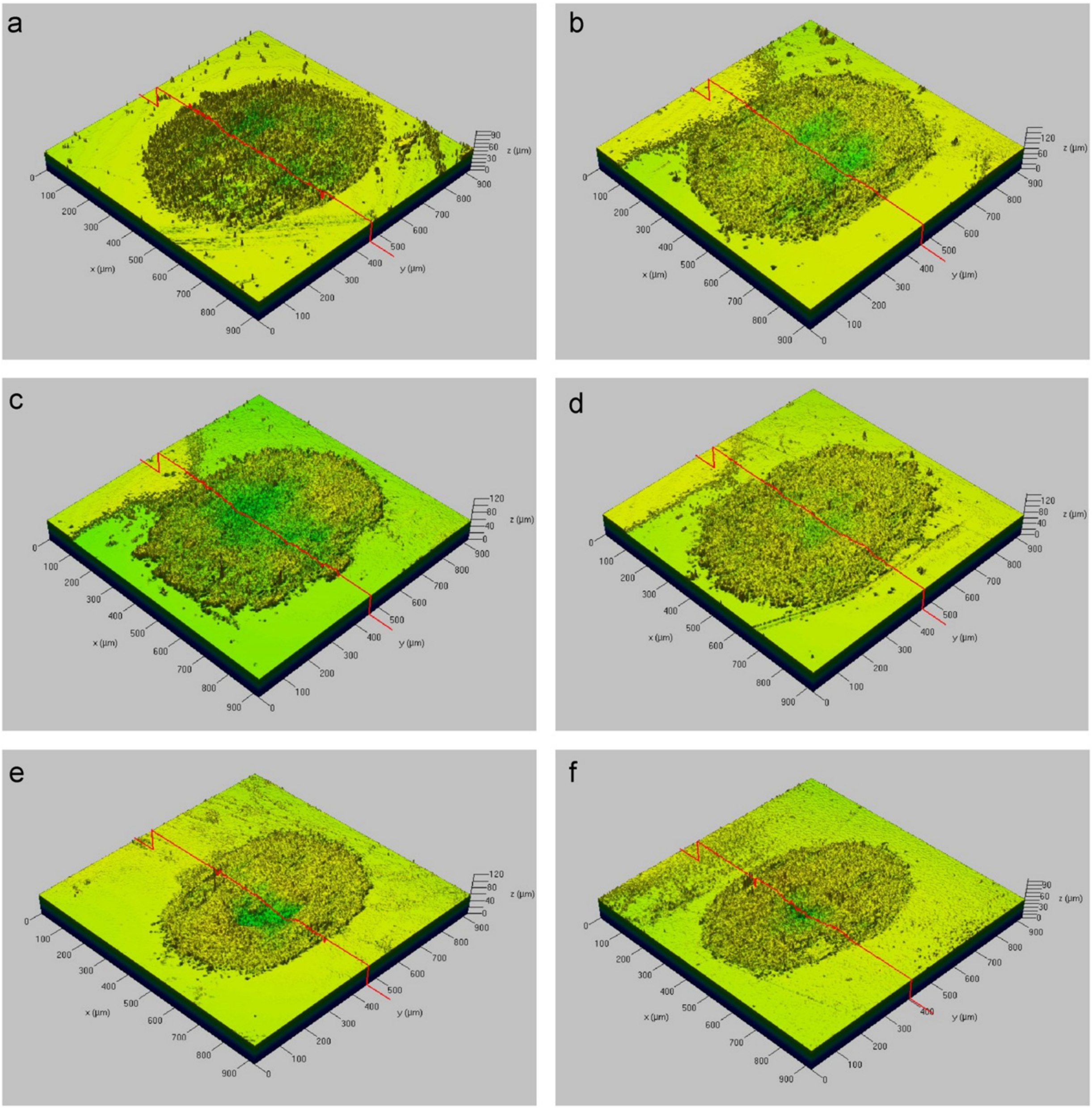


Fig. 13. Three dimensional view of the surface profile of the fretted zone of tin-plated contacts after 20,000 fretting cycles when subjected to fretting corrosion at various temperatures (a) 25 °C; (b) 85 °C; (c) 105 °C; (d) 125 °C; (e) 155 °C and (f) 185 °C.

Table 2
Roughness parameters calculated using the surface profiles of the fretted zone of tin-plated contacts subjected to fretting for 20,000 cycles at various temperatures

Roughness parameter (μm)	25 °C	85 °C	105 °C	125 °C	155 °C	185 °C
Arithmetic mean deviation, (R_a)	1.71	2.77	2.46	2.16	1.96	1.81
Highest peak, (R_p)	28.69	48.91	64.50	31.87	31.34	33.64
Lowest valley, (R_v)	23.68	40.00	37.00	38.45	35.93	29.74
Absolute peak to valley, (R_t)	52.37	88.90	101.50	70.32	67.27	63.38
Average peak to valley,(R_z)	24.56	31.98	22.61	27.47	21.96	19.22
Maximum peak to valley, (R_{max})	52.37	88.90	90.54	57.70	59.73	63.32

shown in Fig. 11. The rate of wear of tin coating is higher at higher normal loads whereas the rate of oxidation is higher at low normal loads. The time to reach the threshold value of contact resistance suggests that the performance of the tin-plated contacts is very poor at low normal load of 0.1 N whereas a higher normal load of 1 or 2 N helps to

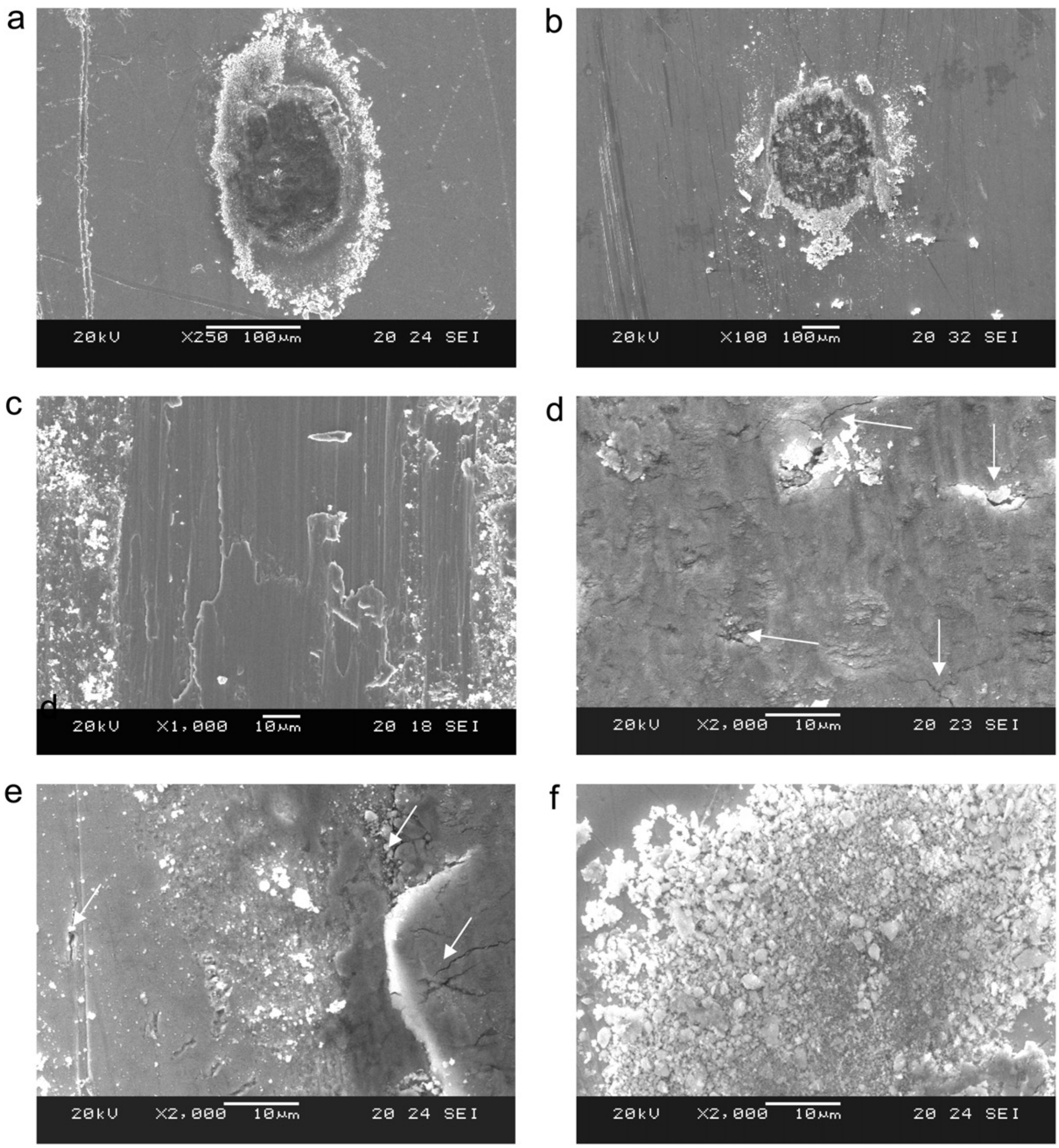


Fig. 14. (a and b) Scanning electron micrographs of the fretted zone of the tin-plated contacts; (c) adhesive wear during the initial stages of fretting cycles; (d and e) delamination at the later stages of fretting cycles (indicated by arrows) and (f) wear debris accumulated at the edges of the fretted zone.

establish a better electrical contact and provides a stable contact resistance for longer fretting cycles. Since the tin-coated contacts contain an oxide layer, a minimal normal load (contact force) is required to break the oxide film and to establish a good electrical contact.

3.2.6. Effect of current load

The effect of current load on the fretting corrosion behaviour of tin-plated contacts is studied in the range of 0.1–3.0 A. The change in contact resistance of tin-plated contacts as a function of fretting cycles obtained at 3 A is shown in Fig. 12. The time to reach the threshold value of contact resistance increases with increase in current load. The performance of the tin-plated contacts is better at current load >1 A as this current load enables to break the oxide film and provides a stable and low contact resistance for longer fretting cycles.

3.3. Surface profile, surface roughness and surface analytical methods of evaluation

The contact zone of tin-plated contacts subjected to fretting corrosion under varying experimental conditions was assessed for their surface profile and surface roughness using LSM. The roughness parameters elucidate the extent of fretting corrosion attack as a function of experimental

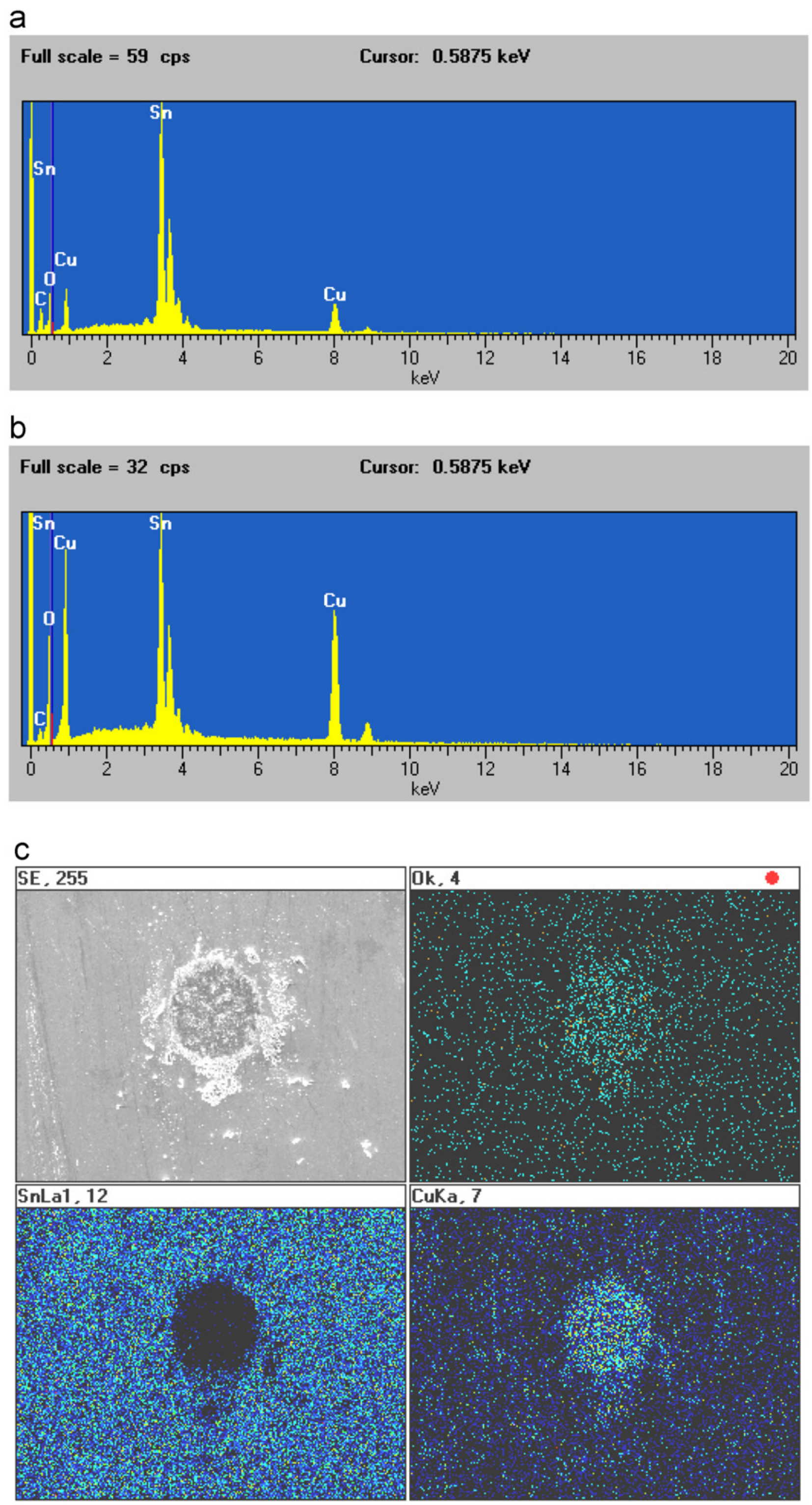


Fig. 15. EDX pattern taken at the edge (a) and centre (b) of the fretted zone of tin-plated contact; (c) X-ray elemental mapping of oxygen, tin and copper of the fretted zone taken after 20,000 fretting cycles indicating the removal of the tin coating and exposure of copper and oxidation of tin and copper.

variables. The three dimensional view of the surface profile of the contact zone of tin-plated contacts subjected to fretting corrosion at 27, 85, 105, 125, 155 and 185 °C are shown in Fig. 13. The roughness parameters calculated from the surface profile are given in Table 2 [28]. The surface morphology of the fretted zone indicates the extent of fretting corrosion attack and the modes of failure such as adhesive wear, delamination, etc. It also reveals the accumulation of wear debris within the contact zone and outside the contact zone [27–30]. These features are shown

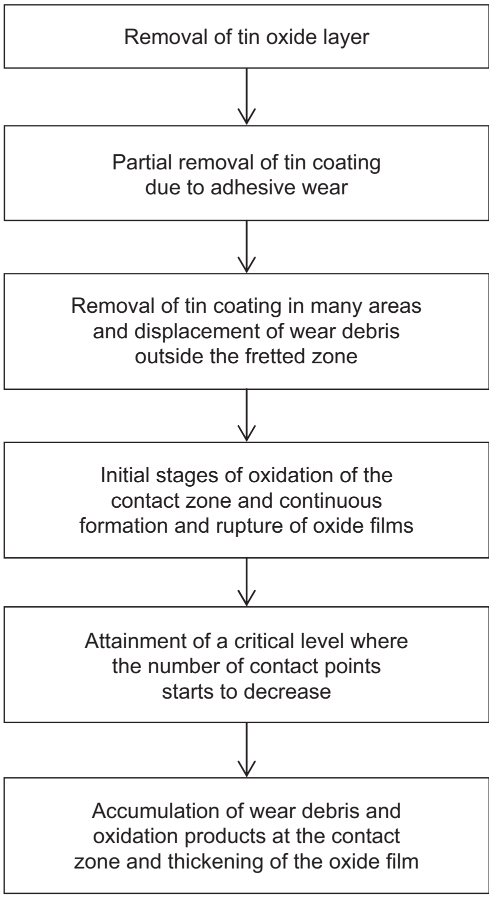


Fig. 16. Schematic of the sequence of changes that the tin-plated contact would encounter with increase in fretting cycles.

in Fig. 14. EDX analysis of the contact zone, spot analysis performed at selected areas and X-ray elemental mapping clearly reveal the nature of chemical species present at the contact zone, the extent of oxidation and accumulation of the debris. Selected EDX and X-ray dot mapping results are shown in Fig. 15.

3.4. Fretting corrosion mechanism of tin-plated contacts

Based on the change in contact resistance as a function of fretting cycles, surface profile, surface roughness and surface analysis using SEM, EDX and X-ray elemental mapping of the contact zone, the mechanism of fretting corrosion of tin-plated contact is proposed [27–30]. The schematic of the sequence of changes that the tin-plated contact would encounter with increase in fretting cycles is given in Fig. 16. As the rate of fretting wear of the tin coating and the rate of oxidation of the contact zone is dependent on many factors, such as, frequency, amplitude, normal load, temperature, humidity, current load, etc., the number of fretting cycles at which the above transitions occur will vary significantly depending on the conditions used. Moreover, the interdependence of extent of wear and oxidation increases the complexity of the fretting corrosion behaviour of tin-plated contacts.

3.5. Development of fretting corrosion maps of tin-plated contacts

A careful analysis of the various stages involved in the fretting corrosion of tin-plated contacts reveals that though oxidation of the contact zone is responsible for the failure of the contact, the fretting wear of the tin coating is initiating the process. Since the fretting frequency is the prime factor that determines the extent of wear of the tin coating, it is considered as one of the prime variable for the development of fretting corrosion maps. Based on the change in contact resistance measured as a function of fretting cycles and, based on the surface analysis of the contact zone, the extent of fretting and oxidation that occurred for various combinations of experimental conditions, are assessed and they are rated in the scale of 1–10; the higher the value of this number (the ratio of the extent of fretting to oxidation) the greater the extent of fretting compared to oxidation. Fretting corrosion tests, for a given set of conditions, can result in the predominant material removal being fretting, oxidation or a combination of both. Hence, segmentation of the various regimes becomes necessary for the construction of the fretting corrosion maps. The fretting corrosion regimes are defined as follows:

$$\begin{array}{ll} \frac{K_f}{K_o} < 0.1 & \text{oxidation-dominant} \\ 0.1 \leqslant \frac{K_f}{K_o} < 1 & \text{oxidation}-\text{fretting} \\ 1 \leqslant \frac{K_f}{K_o} < 10 & \text{fretting}-\text{oxidation} \\ \frac{K_f}{K_o} \geqslant 10 & \text{fretting dominant} \end{array},$$

where K_f and K_o are the extent of fretting and oxidation, respectively. The rationale used is quite similar to the erosion–corrosion mapping methodologies adopted by Stack [14].

Fig. 17 depicts the fretting corrosion maps of tin-plated contacts subjected to fretting corrosion using various combinations of experimental conditions [31]. The fretting corrosion map is segmented into various regimes as oxidation-dominant, oxidation–fretting, fretting–oxidation and fretting wear-dominant, depending on the nature of predominant process for a given set of conditions. Since oxidation of the contact zone is responsible for the failure of the tin-plated contacts, the conditions which represent the oxidation-dominant zone, such as low frequency (3 Hz), low amplitude ($\pm 5\,\mu m$), high temperature (125–155 °C), low normal load (0.5 N) and low current load (0.1 A), could cause a high-risk of failure of the tin-plated contacts [31]. Since the fretting corrosion of tin-plated contacts is a complex phenomenon, it is difficult to predict the exact life-time of such connector contacts using fretting corrosion maps. However, the fretting corrosion maps will be useful to draw some guidelines about the performance of such contacts under different experimental conditions.

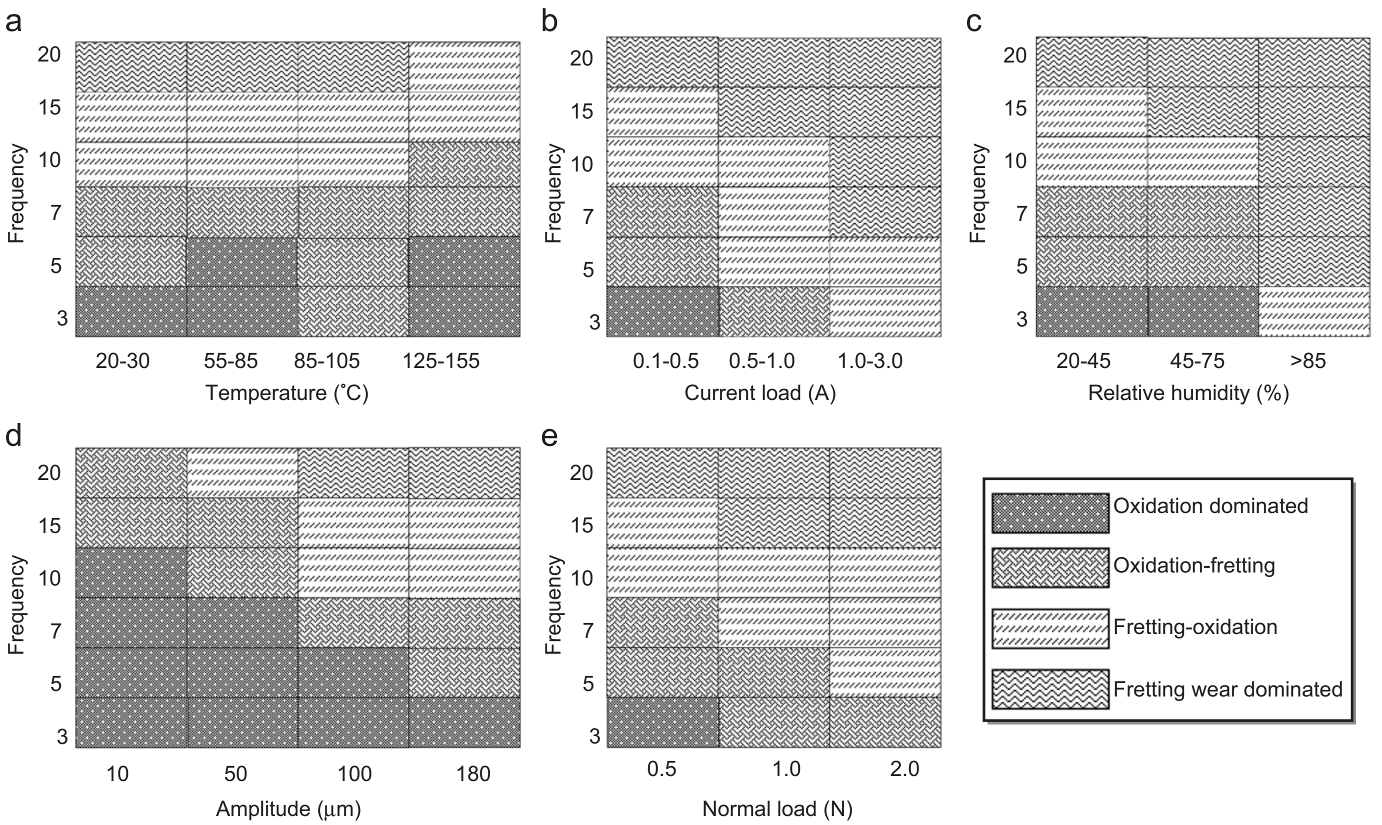


Fig. 17. Fretting corrosion maps of tin-plated copper alloy contacts at various combinations of experimental conditions: (a) 180 μm/50–55% RH/0.5 N/0.1 A; (b) 180 μm/27 °C/50–55% RH/0.5 N; (c) 180 μm/27 °C/0.5 N/0.1 A; (d) 27 °C/50–55% RH/0.5 N/0.1 A and (e) 180 μm/27 °C/50–55% RH/0.1 A.

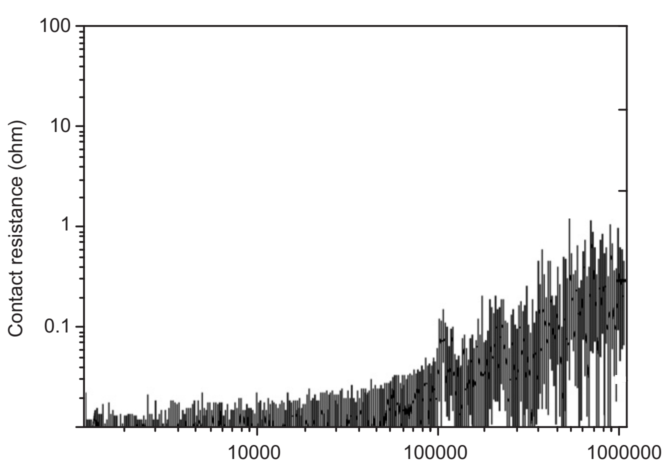


Fig. 18. Change in contact resistance of lubricated tin-plated contacts measured across the contact zone as a function of fretting cycles.

3.6. *Influence of lubrication on the fretting corrosion behaviour of tin-plated contacts*

The effect of a commercial lubricant that consists of a 50–50 mixture of petroleum oil and zinc diamyldithiocarbamate on the fretting corrosion of behaviour of tin-plated contacts is studied. The lubricant film provides a surface coverage of $6.76 \pm 1\,\mathrm{mg/cm^2}$ and it easily establishes metallic asperity contact between the mated tin-plated contacts. The contact resistance of lubricated contacts remains stable for several thousand fretting cycles. Lubricated tin-plated contacts reach the threshold value of $100\,\mathrm{m\Omega}$ only around 100,000 cycles (Fig. 18) whereas unlubricated contact reaches this value around 13,500 cycles itself (Fig. 2). For lubricated contacts, the extent of mechanical wear of the tin coating is significantly reduced. As a result, they experience a lesser damage at the contact zone and exhibit a smoother profile. The formation of tin oxide is not appreciable and there is no oxide accumulation at the contact zone even at 380,000 cycles (Fig. 19). The lubricant is very effective in delaying the fretting wear during the initial stages and in preventing the oxidation and, accumulation of wear debris and oxidation products at the contact zone in the later stages [32].

4. Conclusions

The studies performed to evaluate influence of various factors on the fretting corrosion behaviour of tin-plated contacts leads to the following conclusions:

- The rate of wear of tin coating is higher at higher frequencies whereas the rate of oxidation is higher at lower frequencies.

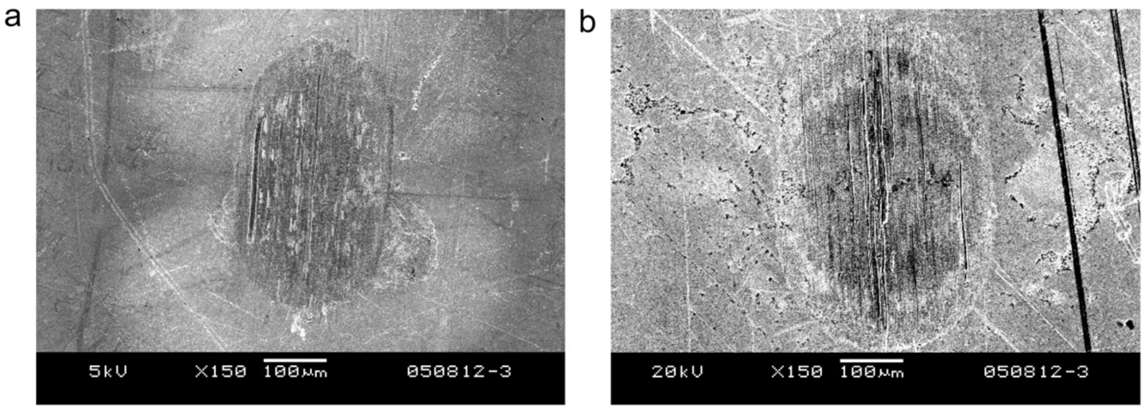


Fig. 19. Surface morphology of the contact zone of lubricated tin-plated contact after (a) 100,000 fretting cycles and (b) after 380,000 fretting cycles.

- The extent of oxidation is very high at higher amplitudes whereas accumulation of debris at the contact zone is higher at lower amplitudes.
- The rate of oxidation is higher at higher temperatures whereas softening of tin around 100 °C enables a better electrical conductivity. The increase in rate of oxidation with increase in temperature and, the high hardness and poor electrical resistance of the Cu–Sn based IMC formed at elevated temperatures, suggests that the tin-plated contacts are unsuitable for high temperature applications.
- The rate of wear of tin coating is less at higher humidity as the condensed water vapour acts like a lubricant.
- The rate of wear of tin coating is higher at higher normal loads whereas the rate of oxidation is higher at low normal loads. Higher normal load helps to establish a better electrical contact. Since the tin-coated contacts contain an oxide layer, a minimal normal load (contact force) is required to break the oxide film and to establish a good electrical contact.
- Higher current load helps to break the oxide film and establish a good electrical contact.

Based on the variation in contact resistance as a function of fretting cycles, surface profile, surface roughness and nature of changes at the contact zone assessed by surface analytical techniques, the mechanism of fretting corrosion and fretting corrosion maps of tin-plated contacts are proposed. Lubrication of tin-plated contacts is a viable preventive strategy to improve the life-time of tin-plated contacts.

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